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A PLAN FOR DEVELOPING AND VALIDATING A GUN SYSTEM DESIGN TRADE-OFF METHODOLOGY

CHARLES F. PRICE
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FEBRUARY 1980

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
FIRE CONTROL AND SMALL CALIBER
WEAPON SYSTEMS LABORATORY
DOVER, NEW JERSEY

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Procedures are described for validating a Helicopter Weapon System Simulation Model (HWSSM) using data collected from the Army's recent Air-to-Air Self Defense Test (AASDT), and for integrating the HWSSM with a gun system sizing model to compute system weight as a function of the basic performance parameters. These parameters include firing interval, probability-of-hit or probability-of-kill, the types of engagements, and the number

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20. ABSTRACT (Continued)

of engagements of each type per mission. These procedures will provide the Army with an overall methodology for conducting airborne gun system design tradeoff studies.

FOREWORD

This project was sponsored by the U.S. Army Armament Research and Development Command (ARRADCOM) under Contract No. DAAK10-79-C-0213. The project officer was Captain John Hirlinger (Code DRDAR-SCS-E), and the principal investigator was Mr. Charles F. Price of TASC.

The authors wish to acknowledge the helpful technical interchanges with Dr. Tonney Hung and Messrs. Richard Dikant and Thomas Hutchings of ARRADCOM.

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1. INTRODUCTION

In the future, U.S. Army attack helicopters will have to have a defensive capability against threat helicopters. One defensive option is an air-to-air gun system and its associated fire control system. To evaluate gun/fire-control system concepts, the capabilities of each concept must be estimated against postulated threats. Insofar as possible this should be accomplished by analysis of realistic, validated gun/fire-control system models.

The Army currently has a Helicopter Weapon System Simulation Model (HWSSM) for airborne gun/fire-control systems which is structurally appropriate for analyzing new system concepts. However, calibration of this model in selected air-to-air engagement scenarios with firing tests of actual systems is required in order to develop an adequate technology data base for extrapolating the models to untested scenarios and gun system designs, with a high degree of confidence. The Army's Air-to-Air Self Defense Test (AASDT), conducted at Fort Bliss, TX, in September 1979, provides data which can serve this purpose.

This report describes procedures for validating the HWSSM using AASDT data. In addition, a technique is presented for combining HWSSM with a gun sizing model to estimate gun system weight required for satisfying specified mission requirements. This provides an overall methodology for trading off gun/fire-control system characteristics such as performance, technology level, rate-of-fire, weight, and single (air-to-air only) vs dual (air-to-air and air-to-ground) mission roles.

2. THE AIR-TO-AIR SELF DEFENSE TEST

The purpose of the AASDT was to evaluate the performance and obtain test data for a state-of-the-art airborne gun system against an airborne target towed by a drone aircraft. The armament system tested was the modified Multiweapon Fire Control System helicopter, an AH-1G Cobra, referred to as the Air-to-Air Test Bed (ATATB). Some significant characteristics of the armament system are:

- Gun: Turreted M197 20-mm Gatling gun (three barrels)
- Ammunition: M55A2 TP & M221 TPT 20-mm rounds
- Sight: Optical with three-axis stabilization
- Rangefinder: Pulsed laser, 4-10 pps
- Fire Control Computer: CDC-469 with 8K memory.

This chapter describes the general test conditions and objectives and the data collected.

2.1 TEST CONDITIONS

The major items of instrumentation for the AASDT were:

- Miss Distance Indicating (MIDI) Radar - Tracks the target and measures the miss distance of each projectile

- <u>Tracking Radar</u> - Tracks the ATATB at a track-point provided by a transponder

- <u>Sight-Mounted Camera</u> - Photographs the target position relative to the stabilized sight onboard the ATATB

- <u>Digital Flight Recorder</u> - Records selected computer data as well as data from aircraft and fire control sensors.

Figure 2.1-1 illustrates the test instrumentation configuration for a typical firing run.

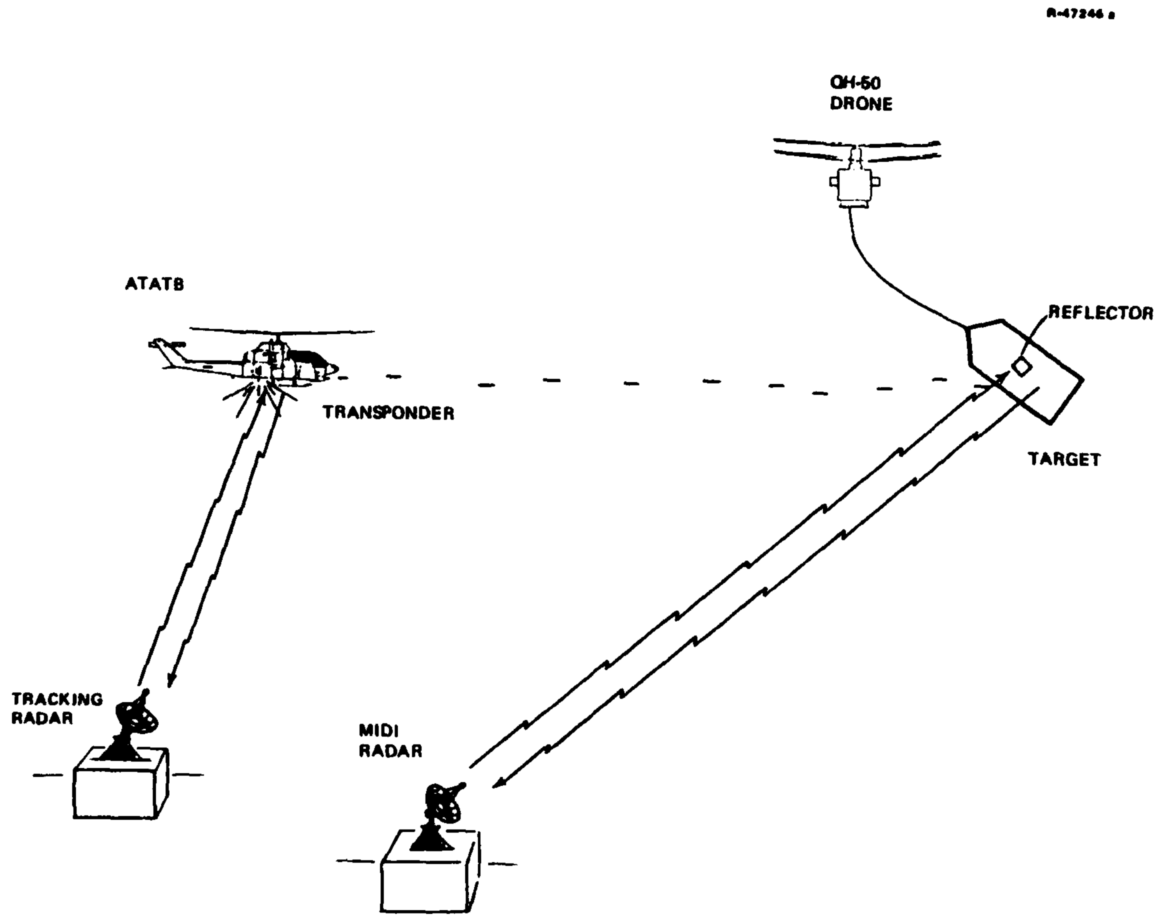

Figure 2.1-1 Test Range Instrumentation Configuration

The target was a 2.4- by 1.2-m (8- by 4-ft) sleeve-covered metal frame towed by a helicopter drone. The frame supported a reflector to serve as a track point for the MIDI radar. The drone was flown in two basic patterns relative to the ATATB. One was a head-on/head-out trajectory where the drone approached, and then turned and retreated from, the ATATB. The other was a crossing pattern where the drone trajectory was perpendicular to the ATATB trajectory. Firing was conducted at different ranges, firing rates (750 and 1500 spm), drone speeds (13 and 26 m/sec -- 25 and 50 kts), and different target aspects yielding both on-axis (firing along the helicopter longitudinal axis) and off-axis firing conditions.

Significant features of the instrumentation are summarized as follows:

<u>Digital Flight Recorder</u>

No. data items recorded = 49

Data rate = 30/7 samples/sec

Real time recording capacity = 11 min

<u>Sight-Mounted Camera</u>

Frame rate = 32 per sec

Capacity ≅ 2 min/magazine; magazines can be reloaded in flight

Accuracy better than 0.1 mrad.

White Sands Missile Range (WSMR), NM, reduced the radar data to provide estimates of ATATB and target positions and velocities, and projectile miss distance statistics for each firing run.

2.2 TEST OBJECTIVES

The overall goal of the AASDT is to develop a data base which can be used to determine those improvements needed in state-of-the-art Army airborne gun systems in order to achieve a defensive capability against attack from an enemy helicopter. Specific test objectives which are to be met in order to achieve the overall goal are:

- Determine the effect of the following on weapon system accuracy (probability-of-hit):

  rate-of-fire
  off-axis vs on-axis firing
  ATATB speed
  target speed
  target range

- Determine the adequacy of the fire control software to handle range and angle dynamics

- Determine the effective engagement range of the M197 gun under AASDT conditions.

The test conditions under which firings were conducted provide the data needed to achieve these objectives. Maximum benefit will be realized from the data by using it to validate HWSSM. The HWSSM can then be used to extrapolate the test results to other modeled engagement scenarios. Ultimately, HWSSM will be applied to detailed analyses of airborne gun system design requirements for defense against helicopter threats.

2.3 DATA RECORDED

<u>Flight Recorder</u> - The ATATB flight recorder data include a number of vector quantities with components expressed

in either an aircraft-fixed rectangular coordinate frame, or in a sight-fixed coordinate frame. The former has its position axes defined as follows in level flight: u_a forward along the longitudinal axis, v_a horizontal and to the left looking forward, and w_a up.* The sight axes, labeled s-ℓ-m, are consistent with the aircraft axes when the sight is stowed in the on-axis position. The following is a list of those quantities included in the data which reflect fire control system operation:

QUANTITY	COORDINATE FRAME
Optical sight position	aircraft
Line-of-sight rates	sight
Gunner's hand controls	sight
Laser measured and predicted range	-
Gun lead angle direction cosines	aircraft
Rate-aided track command	-
Turret rate feedforward commands	-
Estimated aircraft velocity	sight
Estimated aircraft vertical	sight
Track filter range and relative position errors	-
Estimated range and relative position	-
Estimated target velocity and acceleration	sight
Time-of-flight	-
Future range	-
Gravity drop	-

*References 1 and 2 use symbols u, v, w rather than u_a, v_a, w_a; the latter are adopted here to distinguish them from the u-v-w frame defined in the WSMR-reduced data.

The physical meaning of each of the above is defined in Refs. 1 and 2. Twenty data samples were taken for each burst, implying a data-collection interval of approximately 4.7 sec.

Test Range - WSMR processed the data from both the ground-based MIDI and the ATATB tracking radars. Vector quantities are expressed in one of three coordinate frames defined as follows:

- Earth Frame (E-Frame) - east (x); north (y); up (z); centered at the ATATB.
- Normal-Plane Frame (N-Frame) - u-axis along the relative projectile/target velocity vector at the closest point of approach, averaged over the burst; v-axis horizontal and pointing to the left, looking forward along u; w-axis defined by the right hand rule.
- Principal-Axis Frame (P-Frame) - Coordinate frame in which the miss distance covariance matrix, for a given burst, is diagonal.

The following is a list of the quantities included in the data which will be useful for evaluating gun system performance:

QUANTITY	COORDINATE FRAME
Wind speed and direction	E
Target-ATATB relative position	E
Target velocity	E
Gun firing times	-
Individual projectile and target velocities at time of closest approach	E
Individual projectile miss distances	N,E

QUANTITY	COORDINATE FRAME
Burst miss distance statistics	
Mean	E,N
Standard deviation	E,P
E to P direction cosine matrix	
E to N direction cosine matrix	

3. RECOMMENDED TEST DATA UTILIZATION

3.1 STATISTICAL ERROR DETERMINATION

Figure 3.1-1 shows a functional diagram of the ATATB gun system, including various error sources that influence gun system accuracy. The diagram indicates that individual projectile miss distances for any firing interval are accumulated into a dispersion pattern characterized by a bias and "spread". It is implicitly assumed that all of the shots are fired over a short time-period during which there is negligible relative motion of the target and the ATATB. The 0.7-sec firing interval used in the test for each burst satisfies this condition.

Figure 3.1-1 also serves as a functional flow diagram for the HWSSM. The simulation can represent each of the error sources shown in the figure by random number sequences at the appropriate input points in the simulation. In order that the model provide a valid representation of a given test condition, the statistical parameters of each error source must be known. To the extent possible, these parameters should be estimated from the test data.

Because of the short firing interval and the relatively low flight recorder data rates, not all of the error statistics associated with the individual error sources identified in Fig. 3.1-1 can be estimated from the test data with a high degree of confidence. Furthermore, some error sources cannot be separately identified from the test data because of instrumentation limitations. This chapter provides practical recommendations for validating HWSSM within the restrictions imposed by the test conditions.

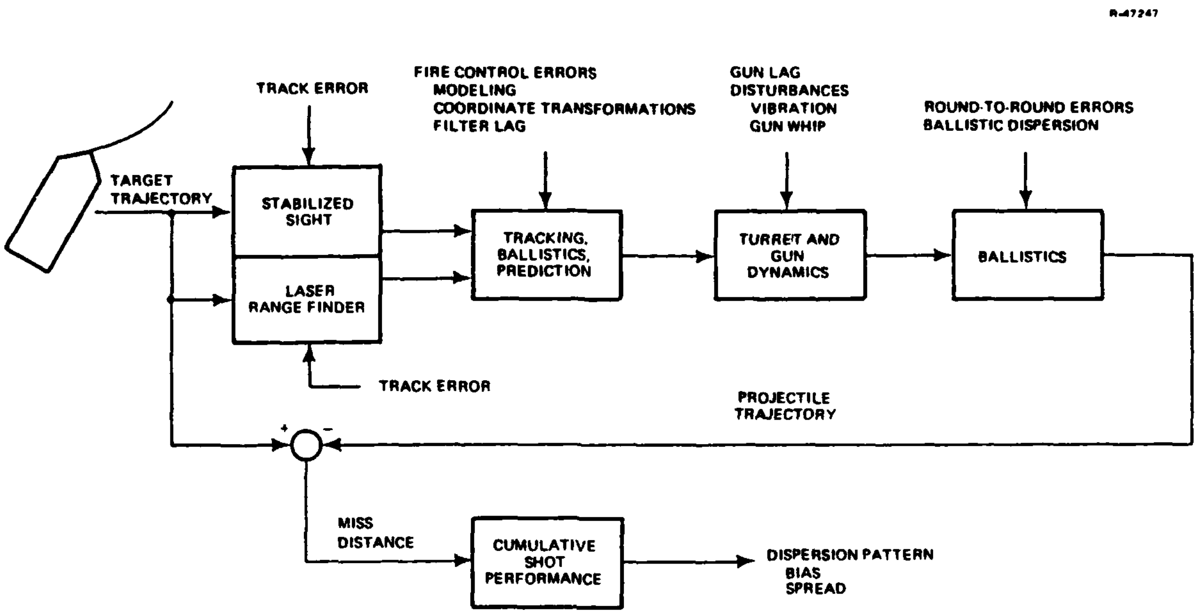

Figure 3.1-1   ATATB Gun System Functional Diagram

<u>Projectile Miss Distance</u> - Projectile miss distance is the ultimate measure of gun system accuracy. The purpose of the model validation effort is to reproduce the miss distance statistics observed during a given firing test run by simulating the same test run with HWSSM.

Miss distance is most naturally measured in a plane normal to the relative velocity between the projectile and the target. The miss vector lies wholly in this plane, so that there is no component of miss distance perpendicular to the plane; this is the sense in which miss distance is usally defined. For a burst consisting of only one shot, the normal plane defines an N-frame in which the miss component along the relative velocity vector (the u-axis) is identically zero. The N-frame defined for the WSMR data is an average over all the shots in a burst; therefore, the u-axis component of the aggregated miss statistics is nearly, but not exactly, zero. This small component can generally be neglected.

The test miss distance statistics are expressed in various forms in the E-, P-, and N-frames. In particular, the mean miss is expressed in the N-frame and the standard deviations are expressed in both the E- and P-frames. This is a result of the manner in which the WSMR data reduction software operates.

The miss standard deviations can be expressed in the N-frame as follows. Let

C_N = the miss distance covariance matrix in the N-frame

T_{PE} = E to P direction cosine matrix

T_{NE} = E to N direction cosine matrix

C_P = the miss distance covariance matrix in the P-frame.

The quantities T_{PE} and T_{NE} are given in the data, and C_P is a diagonal matrix whose diagonal elements are the squares of the P-frame miss distance standard deviations. These standard deviations are also given in the data. Then, it is true that

$$C_N = T_{NE} T_{PE}^T C_P T_{PE} T_{NE}^T \tag{3.1-1}$$

where the superscript "T" denotes matrix transpose. The miss distance standard deviations in the N-frame are the diagonal elements of C_N.

An important issue in validating the HWSSM is the closeness with which a simulation can be expected to reproduce the test results. For example, consider one component of miss distance for which the mean value μ and the variance p are to be estimated. The estimates, $\hat{\mu}$ and $\hat{p}$, are computed from

$$\hat{\mu} = \frac{1}{N} \sum_{i=1}^{N} z_i$$

$$\hat{p} = \frac{1}{N-1} \sum_{i=1}^{N} (z_i - \hat{\mu})^2 \qquad (3.1\text{-}2)$$

where z_i is the i^{th} measurement of the miss component z in a firing run having N shots. If it is assumed that z is a normally distributed random variable, then errors in the estimates are characterized by

$$\sigma_{\hat{\mu}} = \sqrt{E[(\mu-\hat{\mu})^2]} = \sqrt{\frac{p}{N}}$$

$$\sigma_{\hat{p}} = \sqrt{E[(p-\hat{p})^2]} = p\sqrt{\frac{2}{N-1}} \qquad (3.1\text{-}3)$$

Thus, for small values of N, the standard deviations in the estimates of the miss distance mean and variance are significant fractions of their true values.

The errors in the estimated miss distance statistics can be interpreted in terms of confidence intervals. A confidence interval is a range of values about the estimated statistic, within which the true statistic is known to lie with a specified probability. For $\hat{\mu}$ and $\hat{p}$ in Eq. 3.1-2, the intervals are given by (Ref. 3)

$$\hat{\mu} + \frac{t_{0.5\alpha}\hat{\sigma}}{\sqrt{N}} < \mu < \hat{\mu} + \frac{t_{1-0.5\alpha}\hat{\sigma}}{\sqrt{N}} \qquad (3.1\text{-}4)$$

$$\frac{(N-1)\hat{p}}{\chi^2_{0.5\alpha}} < p < \frac{(N-1)\hat{p}}{\chi^2_{1-0.5\alpha}} \qquad (3.1\text{-}5)$$

where $\hat{\sigma} = \sqrt{\hat{p}}$, $1-\alpha$ is the probability that μ and σ^2 are in their designated intervals, and t and χ^2 are the t- and χ^2-distributions which are functions of both α and N-1. Plots of the upper and lower limits of the confidence intervals in Eqs. 3.1-4 and 3.1-5, normalized by $\hat{\sigma}$ and $\hat{p}$, are shown in Fig. 3.1-2.

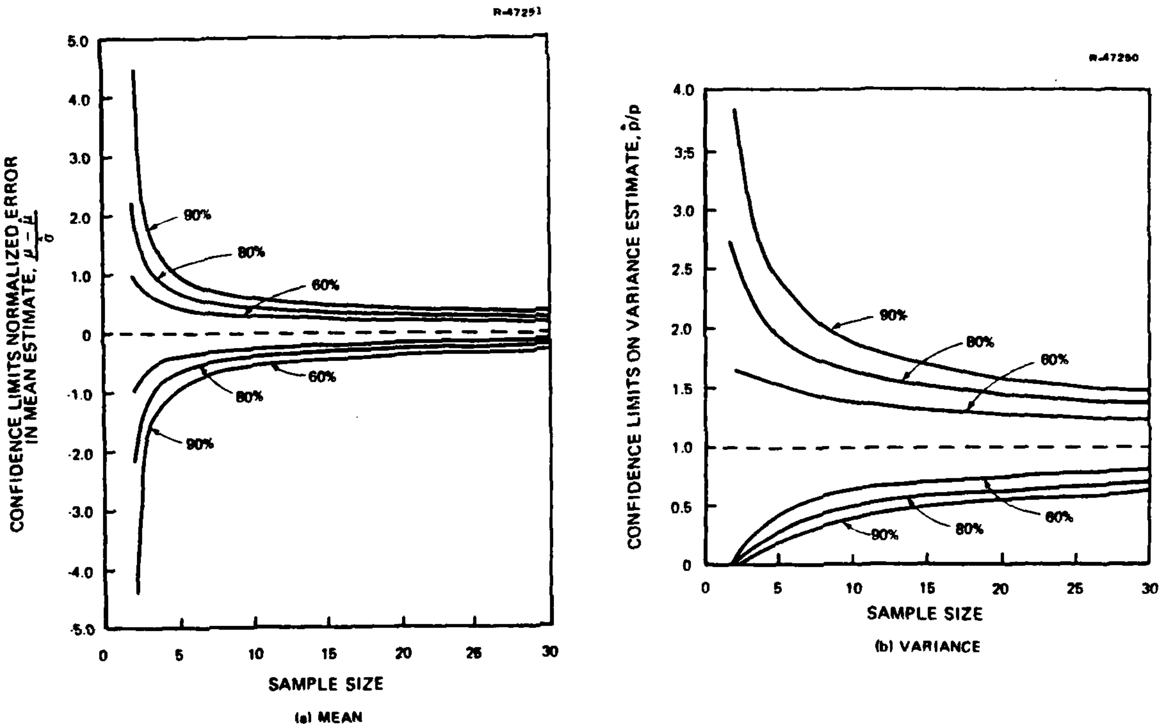

Figure 3.1-2 Confidence Limits for Estimating the Mean and Variance

Each firing interval is 0.7 sec in duration; at firing rates of 750 and 1500 spm, the total number of projectiles fired per interval is approximately 9 and 18, respectively. The curves in Fig. 3.1-2 indicate that μ and p can be estimated to within 30% of $\hat{\sigma}$ and 40% of $\hat{p}$, respectively, with 60% confidence for 9 measurements of projectile miss distance. For 18 measurements, the errors decrease to 20% of $\hat{\sigma}$ and 30% of $\hat{p}$,

respectively. As indicated in the section on "Model Validation Procedure" (Section 3.2), these results have direct implications on how well the output miss distance statistics from HWSSM can be expected to duplicate the results of any given firing test.

<u>Target Tracking Errors</u> - Target tracking error is one of the basic error sources in gun fire control systems. In the ATATB, angle tracking is accomplished with a manually operated stabilized telescope sight. The angle tracking error is thus determined by the gunner's ability to hold the sight on-target. Range tracking is performed by a pulsed laser operating at 4 or 10 pps. Because the fire control solution is updated at 30 Hz, the range measurements are extrapolated at a corresponding 30-Hz rate. Thus there are range tracking errors attributable to both the laser measurements, and to the prediction required between the laser pulse times.

Direct measurements of angle tracking error are available from a sight-mounted camera, operated at 32 frames per second. Because the firing interval is short, it is felt that the tracking error observed just prior to firing is representative of the error during firing, or, more to the point, representative of the tracking error that actually affects the fire control solution during the firing interval, because of the dynamic lags in the fire control software. Therefore, the camera record over a few seconds just prior to actual firing should provide a good statistical sample of the tracking error.

Two components of tracking error are observed in the optical plane of the sight. Over a few-seconds filming period, 100 to 200 separate photographs of the error are taken. If the time-dependence of the error is ignored, the biases and standard deviations of the two tracking error components can be estimated, with the degree of confidence in the estimates

determined in the same manner as for the miss distance statistics.

More generally, the tracking error is really a random process which is influenced by the dynamic behavior of the target and by the gunner's perception and neuro-muscular response to the demands of the tracking task, as well as by the dynamics of the stabilized sight. Thus, the gunner/sight combination can be regarded as a transfer function, as in Fig. 3.1-3, whose input is the relative position between the ATATB and the target and output is the measured relative position. The transfer function is subject to disturbances from base motion, vibration, and firing recoil.

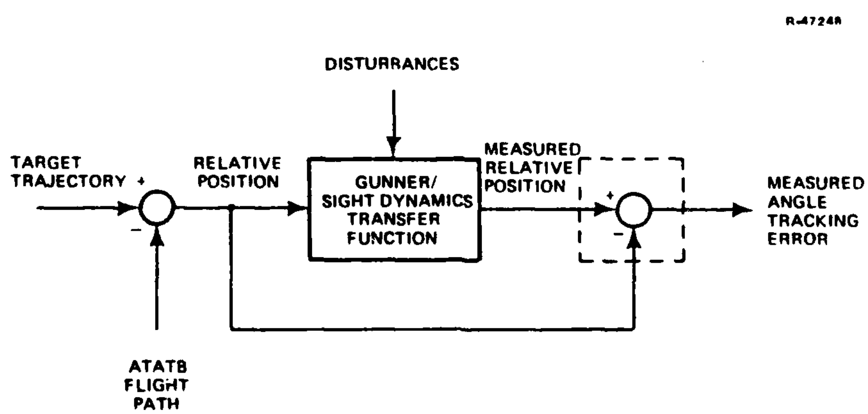

Figure 3.1-3 Gunner/Sight Dynamic Model

One popular model for representing human behavior in a tracking-type task is the cascaded optimal estimator (Kalman filter/predictor)-controller structure illustrated in Fig. 3.1-4. The assumption is that the trained operator learns to act optimally in performing the task. In this case, the parameters of the gunner model would be determined by the known target/sight characteristics. If the gunner is poorly trained for the engagement tested, his model parameters may be unknown;

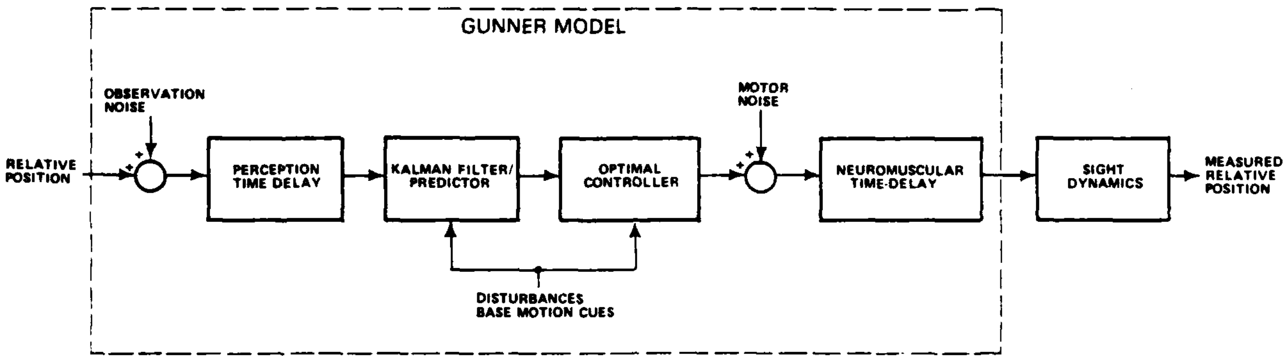

Figure 3.1-4 Optimal Estimator-Controller Gunner Model

in this case they would have to be identified from the test data.

The camera measurements, treated as a time-series, can be used to identify the dynamic parameters of the gunner/ sight transfer function model. This type of data reduction falls in the category of parameter identification for dynamic models. The latter can be accomplished using data processing techniques of varying degrees of sophistication ranging from spectral analysis of the tracking error time-series to the use of optimal estimation methods to identify the model characteristics. These techniques have been used by TASC in several applications, including the type of operator model depicted in Fig. 3.1-4 (Refs. 4, 5, and 6). They require significantly more data processing than simply estimating the mean and standard deviation of the tracking error data sample; however, they provide a means for realistically representing the human tracking function within HWSSM.

It is possible that inherent limitations in manual tracking of an airborne target will suggest a need for automatic tracking. Such a conclusion would require analysis based upon accurate representations of both manual tracking and automatic tracking dynamics in HWSSM. Therefore, it is recommended that the most recent approaches to manual tracking error modeling be reviewed and that a practical, realistic dynamic gunner/sight tracking error model be developed from the test data.

The laser range measurement error can, in principle, be evaluated by comparing the laser measurements with the value of range inferred by differencing the ATATB and target trajectory position measurements provided by the ground tracking radars. However, this procedure is questionable because the laser is inherently more accurate than the radars, and the radar track points on the ATATB and the target do not coincide with the laser location and the laser trackpoint on the target, respectively. Thus, it is likely that the manufacturer's specification for the laser will be the most suitable for use in HWSSM.

The ground tracking data may be useful for determining the error in the computed range at algorithm cycle times between the laser pulse times. In fact, the laser might be used to calibrate the ground data at the pulse times and then the ground data could be used to determine the computed range error at the algorithm cycle times between pulses.

Fire Control Errors - The fire control errors entering the tracking, ballistics, and prediction computation in Fig. 3.1-1 are largely due to approximations in the models used for designing the algorithms, and to the need for filtering to suppress measurement noise. Most of these error sources can be represented in HWSSM by installing the actual ATATB

fire control equations (Ref. 2) into the simulation. Therefore, no direct measurement of these errors is required.

<u>Gun Lag and Gun Disturbances</u> - Gun lag refers to the failure of the gun to "keep up with" a moving target. Gun disturbances include turret vibration induced by the helicopter and by firing recoil. Gun whip is the flexing of the gun barrels with respect to the turret.

The above errors cannot be observed independently from the test data because no measurements are to be taken of the actual turret train and elevation, or of gun barrel motion relative to the turret. The gun lag alone can be represented by including a simplified gun servo model in HWSSM. Thus, a reasonable procedure for isolating the various gun errors is as follows:

- Model the gun servo within HWSSM to represent the gun lag
- Obtain estimates of gun disturbance statistics based upon engineering judgement, available manufacturer's data, or by use of a structural modes simulation such as NASTRAN.

<u>Round-to-Round and Ballistic Dispersion Errors</u> - Round-to-round and ballistic dispersion errors are caused by such random effects as wind gusts and variations in projectile muzzle velocity, mass, and shape. The effects of these errors cannot be isolated from the other errors contributing to projectile miss distance in the AASDT data. However, reasonable estimates of projectile variations should be available from existing ammunition data bases. The combined effects of wind gusts and muzzle velocity variations due to gun barrel wear should result primarily in a component of miss distance bias over the short firing interval.

3.2 MODEL VALIDATION PROCEDURE

Using the procedures outlined in Section 3.1 above, the HWSSM should be modified to incorporate the following features:

- ATATB fire control software
- Turret dynamics
- Gunner/sight tracking error dynamics and disturbance statistics
- Gun disturbances
- Round-to-round errors
- Ballistic effects.

In simulating individual firing runs, the actual ATATB and target test trajectories should be entered into, or approximated in, the HWSSM so that the dynamic conditions encountered during test are realistically represented.

Because only 9 or 18 miss distance samples were collected from each firing interval, depending upon the firing rate, the miss distance statistics obtained from the test can be compared with those derived from the simulation with only limited statistical confidence. The method of comparison is illustrated in Fig. 3.2-1. As indicated, the i^{th} firing test will yield N samples of miss distance, from which the mean and standard deviation of the dispersion pattern, μ_{t_i} and σ_{t_i}, can be estimated. The subscript "t" denotes "test results". Similarly, if HWSSM is used to simulate the i^{th} firing test, estimates of the simulation miss statistics, μ_{s_i} and σ_{s_i}, can be generated, where the subscript "s" denotes "simulation results". However, as noted in the figure, the simulation could be replicated in

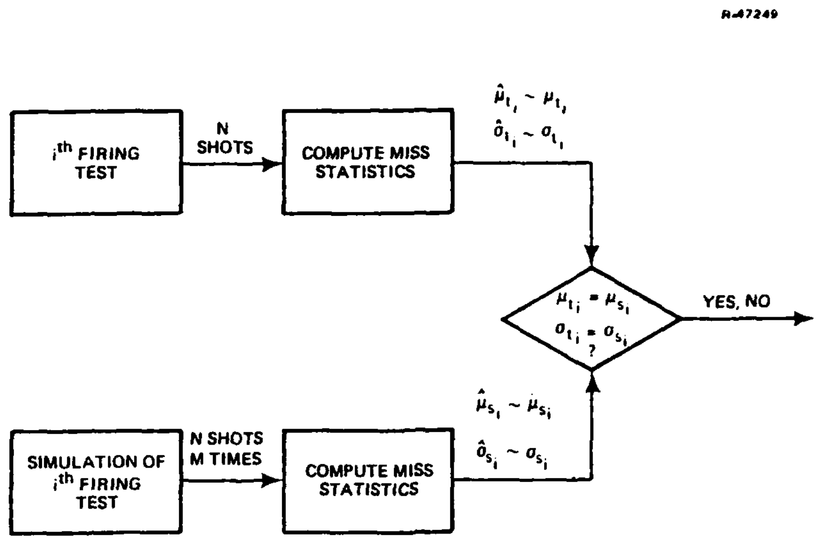

Figure 3.2-1 Procedure for Comparing Firing Test and Simulation Results

monte carlo fashion M-times to provide estimates of the simulation statistics which are as accurate as desired, within the limits of computational feasibility. The outputs of the test and simulation experiments are to be compared, and a decision made as to which of two hypotheses is true for each statistic:

$$H_{\mu_0}: \mu_{t_i} = \mu_{s_i}$$

$$H_{\mu_1}: \mu_{t_i} \neq \mu_{s_i}$$

and

$$H_{\sigma_0}: \sigma_{t_i} = \sigma_{s_i}$$

$$H_{\sigma_1}: \sigma_{t_i} \neq \sigma_{s_i}$$

Acceptance of hypotheses H_{μ_0} and H_{σ_0} would imply that the simulation adequately represents the test.

The first case considered is where the number of monte carlo trials (M) for a simulated firing test is allowed to be large so that

$$\hat{\mu}_{s_i} \cong \mu_{s_i}$$
$$\hat{\sigma}_{s_i} \cong \sigma_{s_i} \qquad (3.2\text{-}1)$$

If Eq. 3.2-1 holds, then the simulation statistics are known and the hypothesis test can be based upon the confidence limits defined in Section 3.1 (Ref. 3). Namely, form

$$\phi = \frac{\mu_{s_i} - \hat{\mu}_{t_i}}{\hat{\sigma}_{t_i}}$$

$$\theta = \frac{p_{s_i}}{\hat{p}_{t_i}}$$

where

$$\hat{\sigma}_{t_i} = \sqrt{\hat{p}_{t_i}}$$

Then

$$\frac{t_{\alpha/2}}{\sqrt{N}} < \phi < \frac{t_{1-\alpha/2}}{\sqrt{N}} \rightarrow \text{Accept } H_{\mu_0} \qquad (3.2\text{-}2)$$

Otherwise, accept H_{μ_1}

and

$$\frac{N-1}{\chi^2_{\alpha/2}} < \theta < \frac{N-1}{\chi^2_{1-\alpha/2}} \rightarrow \text{Accept } H_{\sigma_0} \qquad (3.2\text{-}3)$$

Otherwise, accept H_{σ_1}

for any specified value of α. The latter is the probability of a Type-0 decision error -- i.e., the probability of accepting H_{μ_1} or H_{σ_1} when H_{μ_0} or H_{σ_0}, respectively, is true, is equal to α. Ideally α should be as small as possible; however, the smaller it is, the larger is the probability of making a Type-1 decision error -- i.e., accepting H_{μ_0} or H_{σ_0} when H_{μ_1} or H_{σ_1}, respectively, is true.

Note that the bounds of the test intervals in Eqs. 3.2-2 and 3.2-3 are the same confidence bounds defined in Section 3.1. Choosing $\alpha = 0.4$ roughly corresponds to saying that the simulation and test results are statistically identical when the former falls within the one-σ distribution of the estimated test statistics. This is a reasonable criterion for model validation in the case where the number of test samples is relatively small.

The other case considered is when only a small number of monte carlo simulation trials can be performed, and the resulting uncertainty in the simulation results, $\hat{\mu}_{s_i}$ and $\hat{\sigma}_{s_i}$, cannot be ignored. In order to compare the firing test and the corresponding simulation "test", a confidence limit is needed which reflects the uncertainty in both sets of test results. If we form the quantities $(\mu_{t_i} - \mu_{s_i})$ and (p_{t_i}/p_{s_i}), then appropriate confidence intervals are given by

$$(\hat{\mu}_{t_i} - \hat{\mu}_{s_i}) + t_{\alpha/2}(v) \sqrt{\hat{p}_{t_i} + \hat{p}_{s_i}/M} \Big/ \sqrt{N} < \mu_{t_i} - \mu_{s_i}$$

$$< (\hat{\mu}_{t_i} - \hat{\mu}_{s_i}) + t_{1-\alpha/2}(v) \sqrt{\hat{p}_{t_i} + \hat{p}_{s_i}/M} \Big/ \sqrt{N} \qquad (3.2\text{-}4)$$

$$\frac{\hat{p}_{t_i}}{\hat{p}_{s_i}} \frac{1}{f_{\alpha/2}(v_1,v_2)} < \frac{p_{t_i}}{p_{s_i}} < \frac{\hat{p}_{t_i}}{\hat{p}_{s_i}} f_{\alpha/2}(v_2,v_1) \tag{3.2-5}$$

where $t_{\alpha/2}(v)$ and $t_{1-\alpha/2}(v)$ are values of the t-distribution with

$$v = \frac{(\hat{p}_{t_i} + \hat{p}_{s_i}/M)^2}{\hat{p}_{t_i}/(N-1) + \hat{p}_{s_i}/M^2(NM-1)} \tag{3.2-6}$$

and $f_{\alpha/2}(v_1,v_2)$ is the F-distribution with

$$\begin{aligned} v_1 &= N - 1 \\ v_2 &= NM - 1 \end{aligned} \tag{3.2-7}$$

Again, $(1-\alpha)$ represents the probability that the statistic $(\mu_{t_i} - \mu_{s_i})$ or (p_{t_i}/p_{s_i}) is within the stated confidence interval. Hypothesis tests appropriate for model validation are

$$\frac{t_{\alpha/2}(v)}{\sqrt{N}} < \frac{\hat{\mu}_{s_i} - \hat{\mu}_{t_i}}{\sqrt{\hat{p}_{t_i}+\hat{p}_{s_i}/M}} < \frac{t_{1-\alpha/2}(v)}{\sqrt{N}} \rightarrow \text{Accept } H_{\mu_0} \tag{3.2-8}$$

Otherwise, accept H_{μ_1}

and

$$\frac{1}{f_{\alpha/2}(v_1,v_2)} < \frac{\hat{p}_{s_i}}{\hat{p}_{t_i}} < f_{\alpha/2}(v_2,v_1) \rightarrow \text{Accept } H_{\sigma_0} \tag{3.2-9}$$

Otherwise, accept H_{σ_1}.

The confidence intervals for this case are not plotted here because of their dependence on the test/simulation data. However, they can be readily computed for any given set of test results using the tables of F- and t-distribution values found in many statistics textbooks (e.g., Ref. 7).

The procedures described in this chapter provide a systematic approach to validating the Army HWSSM using the data to be gathered during the AASDT. Subsequently, the HWSSM will be used to investigate air-to-air weapon system design requirements over a broad range of model parameters, and with different fire control algorithm characteristics. This will enable the Army to achieve the maximum benefit from the AASDT in terms of building a technology data base which can be used to develop alternative airborne armament options.

4. GUN SIZING MODEL

A gun system performance model provides a means for analyzing the accuracy with which individual projectiles intercept a target. By accumulating the miss distance statistics over successive shots, in multiple-trial monte carlo analysis of a firing engagement, the cumulative probability-of-hit (P_h) can be calculated; this capability is available in the HWSSM. In addition, if the target vulnerability is characterized in terms of a vulnerable area -- that is, an area in which a hit is assumed to cause a kill -- then P_h can be converted to probability-of-kill (P_k). Vulnerability data for a typical threat are given in Ref. 8.

Gun system sizing refers to the problem of determining what gun system characteristics are required to achieve a specified level of capability against a designated threat. This requires consideration of more than just round-to-round accuracy. In addition, firing rate, firing interval, and required level of P_h or P_k are also important basic design parameters. Ultimately, all such parameters are reflected in the gun system weight. This is one of the most important characteristics of airborne gun systems because of the inherent weight limitations imposed on any aircraft equipment. Therefore it is desirable to express the major components of gun system weight as functions of the basic design parameters. This is accomplished with a gun sizing model. The latter, when combined with HWSSM, provides a methodology for conducting trade-offs among the basic design parameters. This chapter describes the details of a simplified gun sizing model, and

indicates how it can be integrated with HWSSM to provide the trade-off methodology.

4.1 GUN SIZING MODEL

One type of gun likely to be considered for Army airborne applications is the Gatling gun. The gun and its associated mounting equipment, ammunition handling and storage equipment, and ammunition load constitute the major contributions to gun system weight. A number of different types of Gatling guns have been developed, which provide a data base that can be used to develop a gun system weight model. Such a model is described in Ref. 9. A simplified version of the latter is described in this chapter.

For the purpose of this discussion the gun system components are categorized as follows:

- Gun
- Ammunition feed and storage equipment
- Turret and associated structural adapters
- Ammunition load.

The gun weight, w_g is most strongly affected by ammunition caliber, firing rate, and muzzle velocity. Firing rate determines the number of barrels required; muzzle velocity affects the barrel length; and caliber determines the barrel diameter. Based upon the data provided in Ref. 9, a simplified empirical gun weight model is chosen as follows:

$$w_g = 0.45\ c^3\ (a_1+a_2\ c+a_3\ c^2)\ f\ \exp(1.52\ v_m \times 10^{-3}) \quad (4.1\text{-}1)$$

where

$$c = \text{gun caliber in mm}$$

$$f = \text{firing rate in shots/minute}$$

$$v_m = \text{muzzle velocity in m/sec}$$

$$a_1, a_2, a_3 = \text{constants to be determined}$$

$$w_g = \text{gun weight in kg}$$

The values of a_1, a_2, and a_3 are chosen by fitting Eq. 4.1-1 to the data base given in Table 4.1-1, resulting in:

$$a_1 = 8.34 \times 10^{-6}$$

$$a_2 = -5.96 \times 10^{-7}$$

$$a_3 = 1.18 \times 10^{-8}$$

The terms on the right hand side of Eq. 4.1-1 can be partially physically justified by making the following associations

$$\exp(1.52\ v_m \times 10^{-3}) \sim \text{barrel length in calibers}$$

$$c^3 \exp(1.52\ v_m \times 10^{-3}) \sim \text{volume per barrel}$$

$$f \sim \text{number of barrels.}$$

TABLE 4.1-1

GUN WEIGHT DATA BASE
(Source, Ref. 9)

GUN TYPE	WEIGHT (kg)	CALIBER (mm)	MAXIMUM FIRING RATE (spm)	MUZZLE VELOCITY (m/sec)
GAU-8/A	273	30	4200	1060
M61A1	116	20	6000	1050
M197	64	20	3000	1050
GAU-6/A	82	12.7	8000	900

An indication of the validity of the above model is obtained by using it to calculate the weights of guns which are not included in the data base. Two examples are given in Table 4.1-2; the comparison between actual and computed weights demonstrates the usefulness of the model for indicating weight trends as a function of the gun design parameters.

TABLE 4.1-2
EXAMPLE CALCULATIONS WITH THE GUN WEIGHT MODEL

GUN TYPE	ACTUAL WEIGHT (kg)	COMPUTED WEIGHT (kg)	MAXIMUM FIRING RATE (spm)	CALIBER (mm)	MUZZLE VELOCITY (m/sec)
XM-188	68	77	2000	30	700
GAU-2B/A	18.5	20.5	6000	7.62	850

Currently, linked ammunition stored in ammunition boxes is employed in helicopter applications. Adopting a procedure analogous to that used in Ref. 9 for linkless-drum ammunition feed systems, we model the weight of the ammunition handling and storage equipment, w_{as}, as being proportional to the total volume of ammunition carried on board; viz

$$w_{as} = \rho c^2 \ell_r n_r \qquad (4.1\text{-}2)$$

where

ℓ_r = round length (mm)

n_r = total number of rounds carried on board

ρ = density factor

w_{as} = weight in kg.

In general the density factor may be dependent upon ammunition caliber; however, the only available data are for the production 20-mm gun system in the AH-1 helicopter. In that case

$$\rho = \frac{w_{as}}{c^2 \ell_r N_r} = \frac{41 \text{ kg}}{20^2 \times 167 \times 750}$$

$$= 8.2 \times 10^{-7} \text{ kg/mm}^3 \quad \text{(for 20 mm)} \qquad (4.1\text{-}3)$$

There appears to be no available validated model for turret weight as a function of the gun design parameters. Reasoning that turret weight, w_t, should be strongly related to gun weight, we postulate a model of the form

$$w_t = k_t w_g \qquad (4.1\text{-}4)$$

where k_t is derived from the AH-1 turret weight of 82 kg;

$$k_t = \frac{w_t}{w_g} = \frac{82}{64} = 1.28 \qquad (4.1\text{-}5)$$

The remaining gun system component to be modeled is the total ammunition weight, w_a. The latter is simply given by

$$w_a = w_r n_r \qquad (4.1\text{-}6)$$

where w_r is the weight of an individual round.

The total gun system weight, w, is then given by

$$w = w_g + w_f + w_t + w_a \qquad (4.1\text{-}7)$$

As is evident from the above discussion, the components of the weight model have varying degrees of fidelity. The most accurate is w_a and the least accurate is probably w_t. However, the model is useful for indicating weight trends as a function of the basic gun system design parameters.

4.2 DESIGN TRADE-OFF METHODOLOGY

The gun sizing model should be used in conjunction with HWSSM in the following manner. For a given engagement situation, HWSSM can calculate weapon system performance (P_h or P_k) as a function of the firing interval δ and the firing rate f. This relationship is illustrated in Fig. 4.2-1 by the curves of δ vs f for constant values of P_h -- P_{h1}, P_{h2}, etc. Now suppose that δ_0 and P_{h1} are the desired system design parameters. The HWSSM output curves indicate that a firing rate f_0 is required; this simultaneously determines the number of rounds n_0 to be fired during δ_0,

$$n_0 = f_0 \delta_0$$

The total projectile load can now be specified in terms of the maximum number of threats n_t to be engaged per mission,

$$n_r = n_0 n_t$$

The projectile and gun design parameters together with f_0 and n_r are now used in the sizing model described in Section 4.1 to calculate the corresponding total gun system weight, w_0. This result is illustrated in the graph of weight vs firing interval at the bottom of Fig. 4.2-1; the overall functional flow of the trade-off methodology is shown in Fig. 4.2-2.

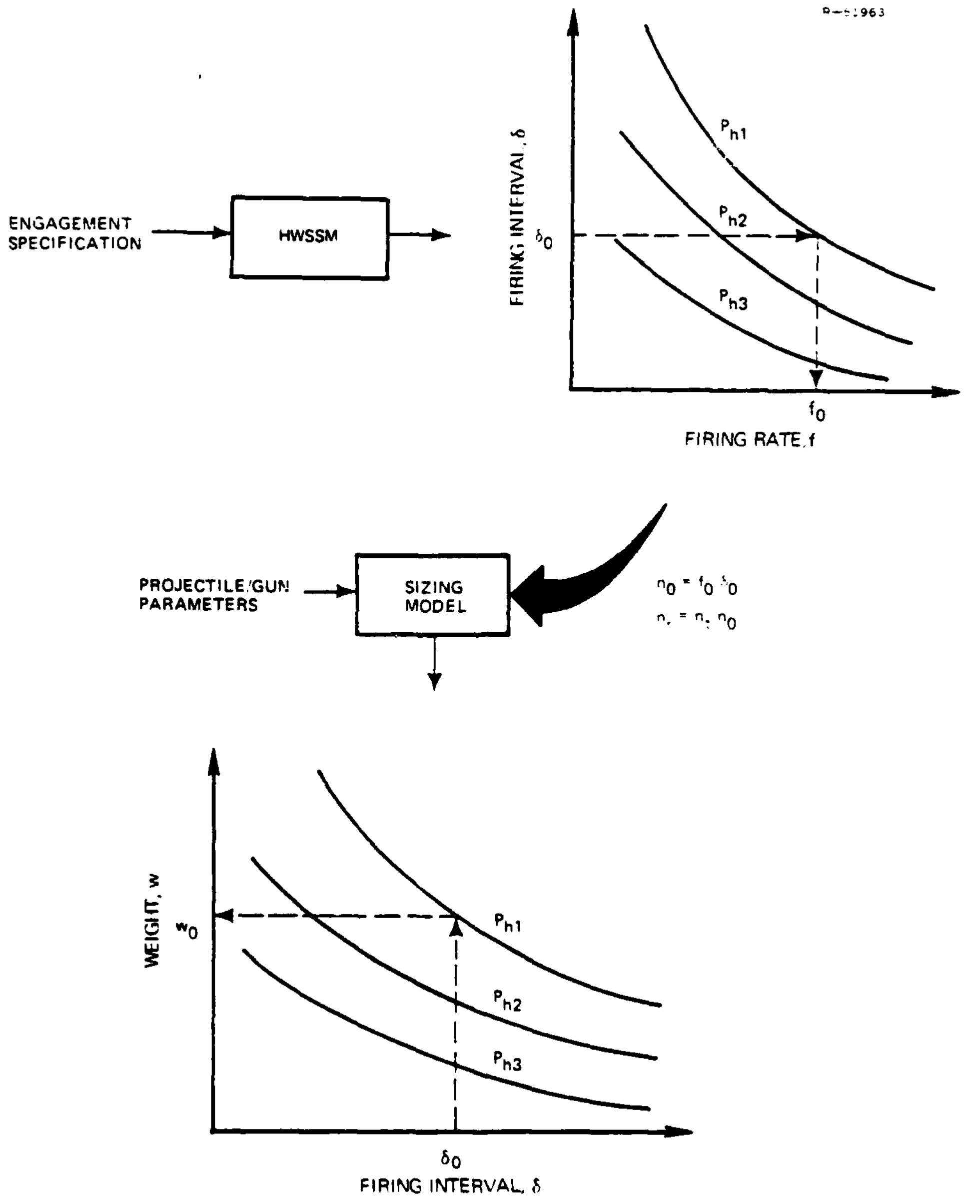

Figure 4.2-1   Steps in the Design Trade-Off Methodology

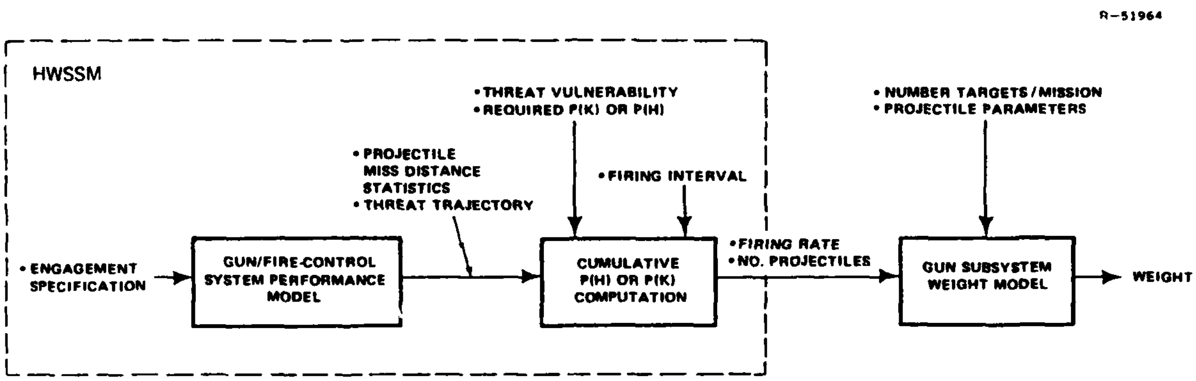

Figure 4.2-2 Functional Flow of Design Trade-Off Methodology

In the above discussion, the firing interval, P_h (or P_k), and gun system weight are viewed as the most important measures of gun system effectiveness and "cost". The firing interval required to achieve a given level of P_h or P_k is important in defensive air-to-air engagements because it determines how much time the enemy has to counterattack, thereby directly affecting own-aircraft survivability. Firing time may also be important in air-to-ground offensive operations for ensuring target destruction before ground-based defenses can be brought to bear. Gun system weight is an important measure of "cost", because of the limited armament-carrying capability of a helicopter.

Although the discussion above assumes that the gun system is sized based upon performance requirements for a number (n_t) of identical threat situations, the total number of rounds n_r and hence the total weight, can be based upon multiple engagement/mission requirements. That is,

$$n_r = n_{t_0} n_0 + n_{t_1} n_1 + \dots + n_{t_k} n_k$$

where the subscripts denote different air-to-air and air-to-ground scenarios. Thus the output of HWSSM and the gun sizing model can identify important trade-offs in multi-mission roles.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 SUMMARY AND CONCLUSIONS

This report describes procedures for validating a Helicopter Weapon System Simulation Model (HWSSM) using data collected from the Army's recent Air-to-Air Self Defense Test (AASDT), and for integrating the HWSSM with a gun system sizing model to compute required system weight as a function of the basic performance parameters -- firing interval, probability-of-hit or probability-of-kill, the types of distinct engagements, and the number of engagements of each type per mission. The principal results and conclusions of this work are as follows:

- Procedures for identifying models of the various gun system errors from the AASDT data are described
- Confidence limits for estimated error statistics are characterized; projectile miss distance confidence intervals are relatively large (on the order of ±30% of the estimated statistics) because of the small number of projectiles fired per burst
- The HWSSM can be validated by simulating the AASDT engagements and comparing the model output miss distance statistics with those observed in the actual test. The determination of whether HWSSM correctly represents the test results is posed as a hypothesis test
- A gun system weight model is presented which represents weight as a function of basic system design/performance parameters.

5.2 RECOMMENDATIONS

It is recommended that the procedures outlined in this report for validation of HWSSM and development of a gun system design methodology be implemented. The work items to be completed include:

- Analysis of the AASDT data to determine projectile miss distance statistics and an appropriate statistical tracking error model as functions of the engagement parameters
- Modification of HWSSM to incorporate models of the test system fire control equations and error sources
- Validation of the HWSSM for selected AASDT engagement scenarios
- Integration of the gun sizing model with HWSSM.

This effort will result in a simulation tool that will be useful for extrapolating the AASDT results to other engagement scenarios, and for analyzing the design trade-offs needed to arrive at specifications for a new airborne gun system.

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